

CHAPTER 9

COASTAL ENGINEERING



NOTE: For trunkline projects, direct questions and comments to the Hydraulic Unit Supervisor, Environmental Services Section.

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If you require assistance accessing this information or require it in an alternative format, contact the Michigan Department of Transportation's (MDOT) Americans with disabilities Act (ADA) coordinator at Michigan.gov/MDOT-ADA.

9.1 INTRODUCTION/PURPOSE

Coastal roads and bridges are influenced by their presence in or near the water level, wave, and sediment transport environment unique to a coast. While normally associated with the oceans, the coastal environment includes the Great Lakes and other water bodies affected by coastal storms and waves.

Many different natural processes and forces impact roads and bridges near the coast. Challenges for coastal roads and bridges include the following:

- Water level – seasonal and multi-year fluctuations due to precipitation and evaporation.
- Storm surge –temporary rise in water level along the coast in response to storm winds and pressures (including seiches on the Great Lakes).
- Waves –forces that affect roadways and bridges and can cause significant damage when superimposed on a storm surge.
- Shoreline erosion – a process where land at the edge of a body of water is worn away by natural forces like waves, currents, and wind; compromising nearshore roadways by undermining or overtopping.
- Littoral Drift – longshore currents transport sediment down the coast changing shorelines, moving channels and streams, and potentially impacting nearshore roadways and bridges.

This chapter covers the design criteria for coastal infrastructure projects and offers guidance on determining design parameters such as stillwater elevation, design wave height, and revetment design. The impact that lake level and coastal storms have on road and bridge overtopping, scour, shoreline erosion, and potential structural damage to superstructures are discussed.

9.2 DEFINITIONS

Annual Exceedance Probability (AEP) - The probability that the magnitude of the random variable (e.g., annual maximum water level) will be equaled or exceeded each year, often expressed as a percentage.

Annual Recurrence Interval (ARI) - The average time interval between occurrences of an event of a given or greater magnitude, usually expressed in years. The ARI is the reciprocal of the AEP of an event.

Armor Layer - Protective layer of rip rap on the outside or top of a revetment or seawall composed of armor units. The armor layer is one of three components of revetment design.

Breaker Zone - The zone within which waves approaching the coastline commence breaking caused by the reduced depths.

Coastal Roadway - Roads influenced by their presence in or near the water level, waves, and sand transport environment unique to a coast.

Depth-limited - Wave height is limited by the local depth of water.

Design Wave Condition - A wave condition with a specified return period used in the design of coastal infrastructure. It is superimposed on the stillwater elevation.

Fetch - The uninterrupted distance or area in which wind blows across the water in a constant direction forming waves.

Freeboard - The vertical distance between the design water surface elevation and a point of interest such as a low chord of a bridge beam, crown of a culvert, or specific location on the roadway grade, for example, the bottom of subbase grade.

Geotextile - Synthetic non-woven fabric used as the base layer in revetment design.

Littoral Drift - The movement of sediment parallel to the shoreline driven by breaking waves and longshore current.

Longshore Current - The littoral current in the breaker zone moving essentially parallel to the shore, usually generated by waves breaking at an angle to the shoreline.

Meteotsunami - Long-wave motions principally caused by meteorologically-induced disturbances, including those associated with pressure jumps, frontal passages, and squalls.

Normal Water Level - The surface of the water if all wave and wind action were to cease. It is also referred to as quiescent water level.

Overtopping - Passing of water over the top of a structure or roadway as a result of an elevated lake level, wave runup, or surge action.

Revetement - A layer or layers of stone, concrete, etc., to protect an embankment, or shore structure, against erosion by wave action or currents. Riprap used in coastal revetment design often consists of heavier stone than riverine riprap.

Scour - Erosion of streambed or bank material due to flowing water; often considered as being localized around piers and abutments of bridges. (23 CFR § 650.305)

Seawall - Structure, often concrete or stone, built along a portion of a coast to prevent erosion and other damage by wave action. Often it retains earth against its shoreward face.

Seiche - A standing wave oscillating in a body of water that continues, in pendulum fashion, after cessation of the originating force. Seiches are caused when strong winds and rapid changes in atmospheric pressure push water from one end of a body of water to the other.

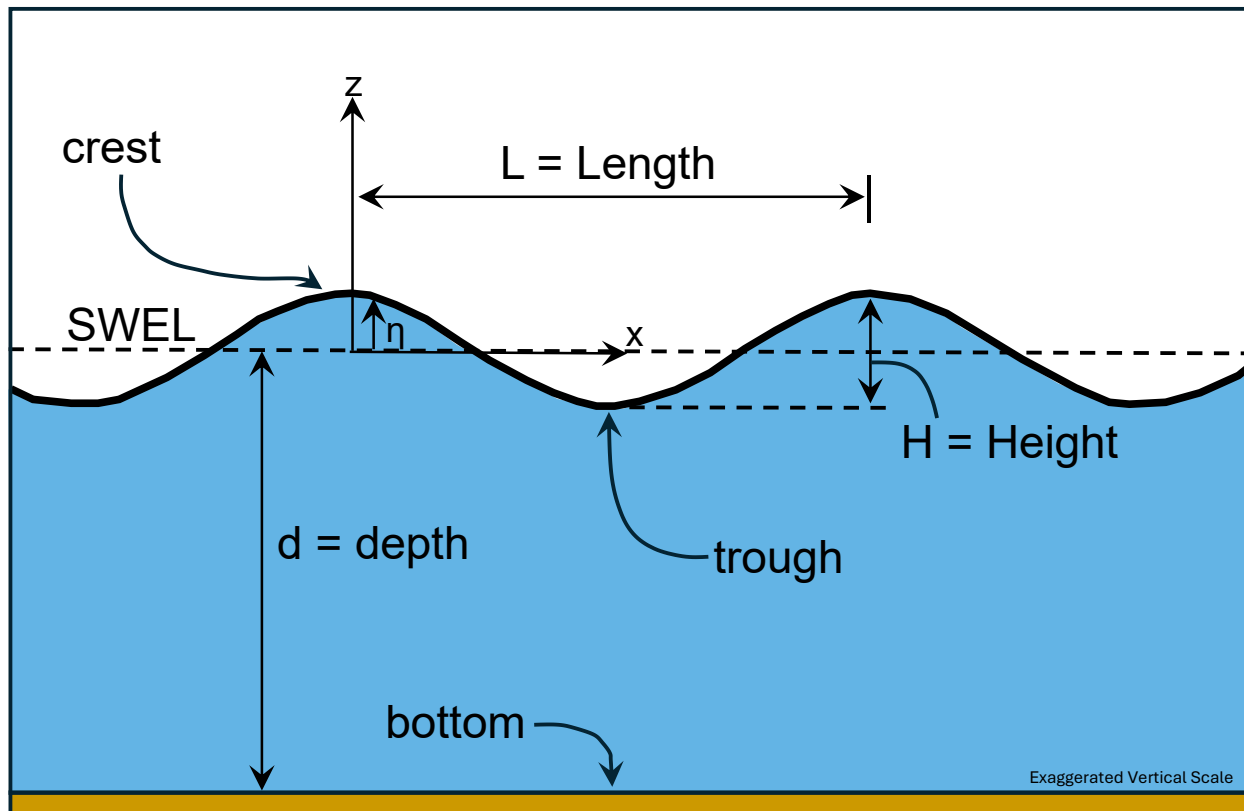
Shallow Water - Shallow water refers to areas where the water depth is less than $1/20$ of the wavelength of surface waves and the bottom topography significantly affects wave propagation.

Significant Wave Height - The primary measure of wave height in an area that is not influenced by the lake bottom. This wave height is calculated as the average of the highest 33% of waves.

Stillwater Elevation (SWEL) - The water level that includes the normal water level with influence of a storm surge and wave setup but does not include wave height. SWEL can vary depending on the fluctuations in normal water level. HEC-25 refers to stillwater elevation with the acronym SWL.

Storm Surge - A rise in water level above the normal level due to the action of a storm. Storm surge results from wind stress and changes in atmospheric pressure.

Wave - A ridge, deformation, or undulation of the surface of a liquid. Refer to **Figure 9-1**.

Figure 9-1. Wave Parameter Definitions (FHWA HEC-25, 2020)

Wave Crest - The highest part of a wave measured from the still water level to the top of the wave. Refer to **Figure 9-1**.

Wave Height (H) - The vertical distance between a crest and the preceding trough. Refer to **Figure 9-1**.

Wave Period - The time period between arrivals of successive wave crests at a point (typically 3-5 seconds in the Great Lakes).

Wave Runup - The elevation reached by a wave on a beach or coastal structure relative to SWEL.

Wavelength (L) - The horizontal distance between similar points on two successive waves measured perpendicular to the crest. Refer to **Figure 9-1**.

A list of symbols and acronyms used in this chapter is provided in **Appendix 9-A**.

9.3 POLICY AND DESIGN CRITERIA

Design criteria establish the standards by which a policy is placed into action. They form the basis to select the final design configuration. Examples of policy and design criteria for coastal design are provided in this section.

9.3.1 Federal Policy

For federal policy, refer to Chapter 2, Legal Policy and Procedure.

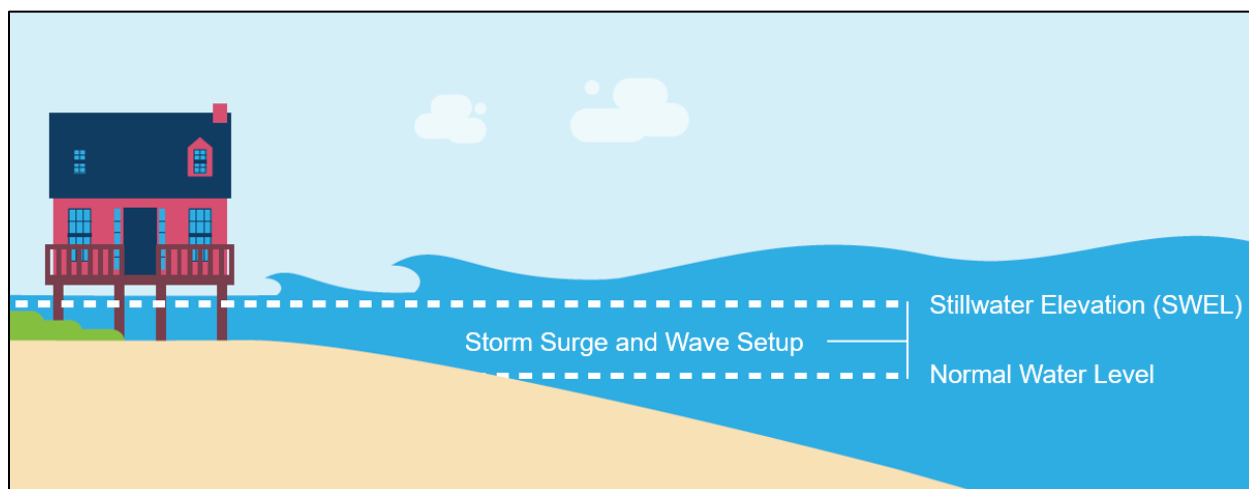
9.3.2 State Policy

For state policy, refer to Chapter 2, Legal Policy and Procedure.

9.3.3 Design Criteria

The selection of a design stillwater elevation (SWEL) is one of the most important coastal engineering decisions for roadway infrastructure. The SWEL includes the influence of storm surge and wave setup superimposed on the normal water level. It does not include wave height. The higher the SWEL, the farther inland the impacts of flooding occur. Similarly, the higher the SWEL the further inland waves will impact structures. The SWEL is shown in **Figure 9-2**.

Figure 9-2. Stillwater Elevation (modified from FEMA)



In coastal engineering projects, a design SWEL AEP is selected based on roadway classification and average daily traffic (ADT), measured in vehicles per day. **Table 9-1** summarizes the AEP design criteria for roadway inundation and revetment design in coastal areas. A greater level of protection may be needed for roadways that require access during flooding events regardless of the ADT. This can be determined by the criticality of the roadway or structure. The following, derived from AASHTO Specifications, defines the roadway or structure criticality:

- **Critical infrastructure** – Roadways and bridges are considered critical when they are expected to be open and useable by emergency vehicles and for security, defense, economical, or secondary life safety purposes during or immediately after the design AEP. These roadways are designed to withstand wave impacts, avoid overtopping, and resist the undermining of embankment due to erosion for the design AEP. Critical roadways are expected to be open to all traffic within days of an event.
- **Noncritical infrastructure** - Roadways and bridges are considered noncritical when they are not expected to be used immediately after the design AEP. Critical roadways use a lower frequency AEP than noncritical roadways. Due to the uniqueness of each roadway, use the design AEP where practicable for noncritical roadways.

Table 9-1. Roadway Minimum Design Criteria AEP

Asset Type	ADT (VPD)	Design AEP (ARI)
Inundation on MDOT Roadways	> 2000	1% (100-year)
Inundation on MDOT Roadways	≤ 2000	2% (50-year)
Inundation on Local Roadways	> 2000	4% (25-year)
Inundation on Local Roadways	≤ 2000	10% (10-year)
Revetments	All	1% (100-year)

9.4 DESIGN GUIDANCE AND PROCEDURE

9.4.1 Determining High Water Levels

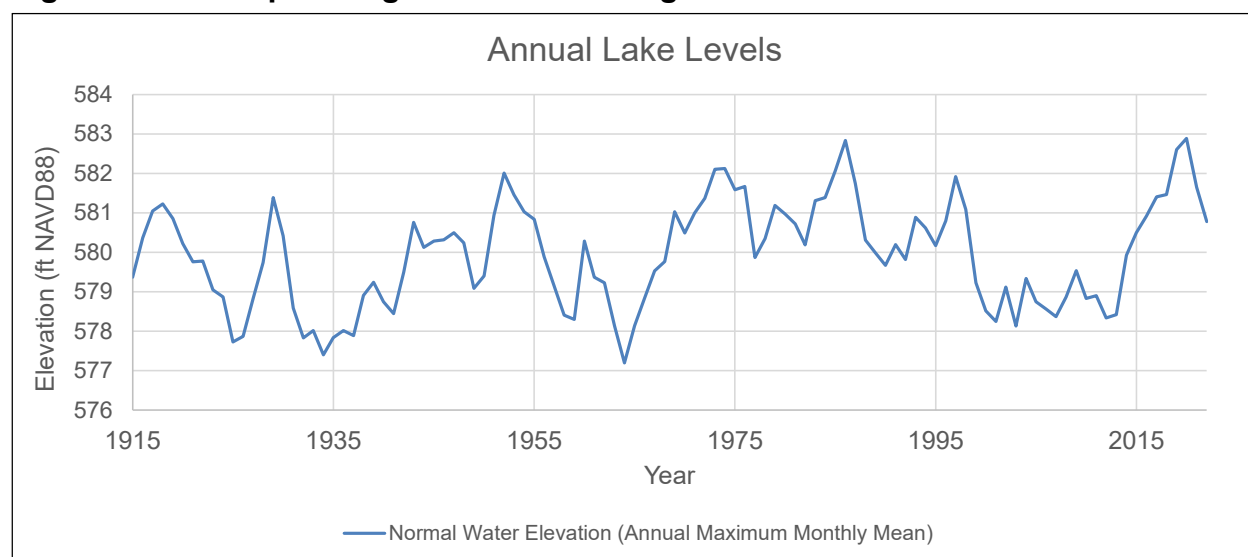
Water levels on the Great Lakes fluctuate with changes in weather, seasons, and the changing climate. NOAA/NOS and the U.S. Army Corps of Engineers (USACE) records and tracks the water levels of the Great Lakes. The Great Lakes water levels use the International Great Lakes Datum (1985). Convert the water level to the project vertical datum. The measured water level is used to determine normal water levels, SWEL, and the extent of wave impact which is an important component for coastal infrastructure design.

9.4.1.1 Seasonal and Historical Fluctuations

The Great Lakes water levels follow a seasonal cycle. In the fall, water freezes and becomes snow and ice which reduces flow into the lakes lowering water levels. In the spring, the snow and ice melt and rainfall increases which lead to higher water levels in the summer. Lake levels generally change 1-2 feet from season to season within any given year.

Great Lakes water levels fluctuate several feet between periods of high water and low water over decades. During long-term periods of dry weather, lake levels fall. When precipitation remains above average, water levels rise. Evaporation plays a role in lake levels. Average monthly pan evaporation rates are relatively predictable. Ice cover on the lakes can significantly reduce evaporation rates. An example of long-term measured Lake Michigan levels converted to vertical datum NAVD88 is shown in **Figure 9-3**.

Figure 9-3. Example Long-Term Lake Michigan Level



9.4.1.2 Storm Surge and Seiche on the Great Lakes

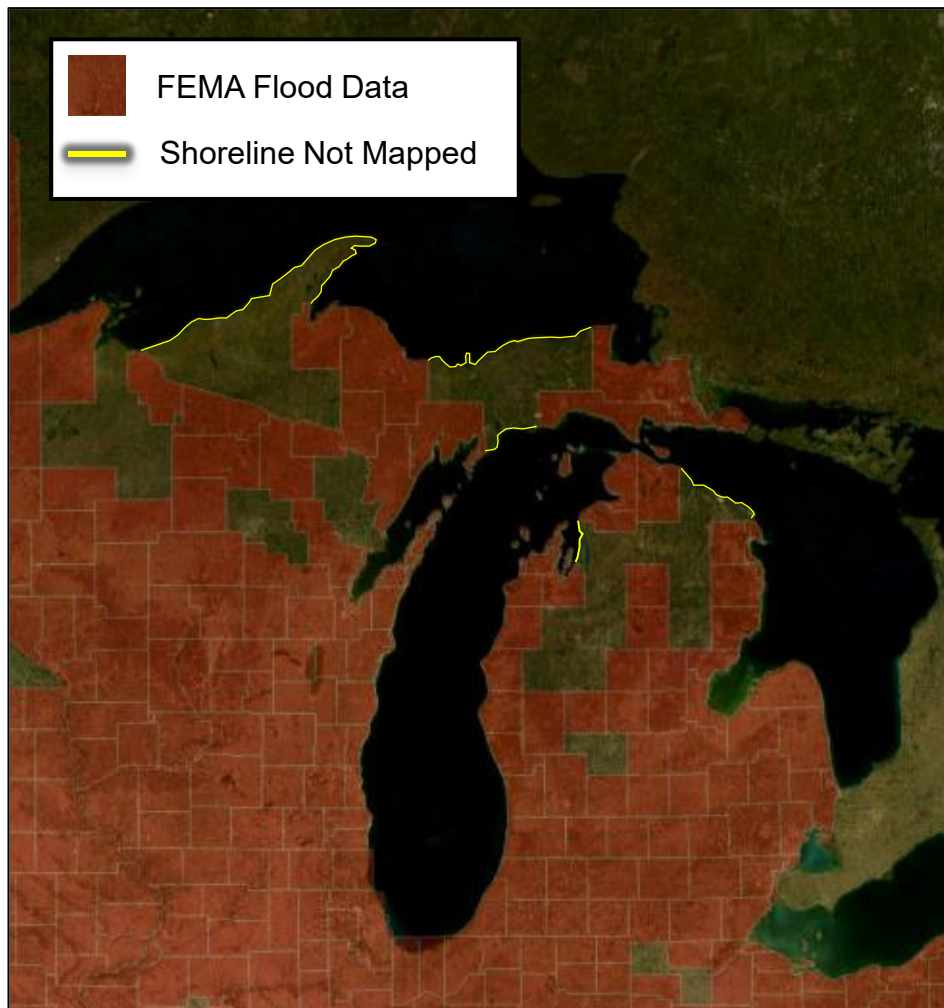
A storm surge is the rise of the water level above the normal water level because of weather. A storm surge on the Great Lakes can present as a phenomenon called a seiche. A seiche is a long-period (several hours) standing wave oscillating in a body of water across an entire lake basin. Seiches are caused when strong winds and rapid changes in atmospheric pressure push water from one end of a body of water to the other. The water oscillates from one end to the other until it returns to its normal water level.

Basin characteristics affect the frequency and severity of a seiche. If a basin is oriented in the same direction as the path of a storm, the wind blows across the surface over a greater distance and increases the magnitude of a storm surge and a seiche may occur. In the Great Lakes area, storms often move from west to east, which is why Lake Erie is particularly susceptible to seiches.

Seiches can cause the water level to change by several feet in a short amount of time. Seiches can reach more than 10 feet and take as long as 8 hours to oscillate back and forth. Storm surge elevations vary significantly from location to location. The impact of seiches on shorelines and roadway structures can cause significant damage.

9.4.1.3 Determining Design Stillwater Elevation (SWEL)

The design SWEL can be determined from several sources depending on the design requirements. In designs that require the 1% AEP SWEL, FEMA has compiled the [National Flood Hazard Layer \(NFHL\)](#) dataset available in an online map viewer. The NFHL Viewer includes flood data for the country, including areas marked as Zone VE, which are coastal areas with a 1% or greater chance of flooding and an additional hazard associated with storm waves. In Zone VE, the flood elevation provided includes the SWEL and the wave height. **Figure 9-4** shows the areas in Michigan that have flood data available as of 2025.

Figure 9-4. FEMA NFHL Viewer (as of 2025)

As of 2025, there are areas in Michigan that have not been mapped. These unmapped areas are outlined in yellow **Figure 9-4**. In these areas a statistical analysis of historical storm surge elevations at a specific site is required to determine the 1% AEP SWEL. A statistical analysis is performed to determine higher frequency SWELs. The Log-Pearson Type III distribution is applied to long term lake level data to predict the design SWEL. Other statistical distribution methods may be applied with approval from the Hydraulic Unit Supervisor on trunkline projects. Long term lake level data is obtained from NOAA or USACE. The monthly mean data is used to determine the normal water level. The monthly peak data is used to determine the SWEL.

Example:

Using the NOAA website, over 100 years of annual lake levels were downloaded for a Lake Michigan gauge. Determine the design SWEL for a range of AEP using the Log-Pearson Type III distribution.

The monthly mean is used to establish the normal water level. The monthly maximum data is used to determine the SWEL. The monthly mean and monthly max data for the gauge is shown in **Figure 9-5**. The Log-Pearson Type III distribution is applied to both sets of data following the guidelines set out in USGS *Bulletin#17C: Guidelines for Determining Flood Flow Frequency* (2019). The normal and stillwater elevations are compiled in **Table 9-2** for a range of AEP frequencies. The normal and stillwater frequency curves are plotted in **Figure 9-6**.

Figure 9-5. Michigan Lake Level Data

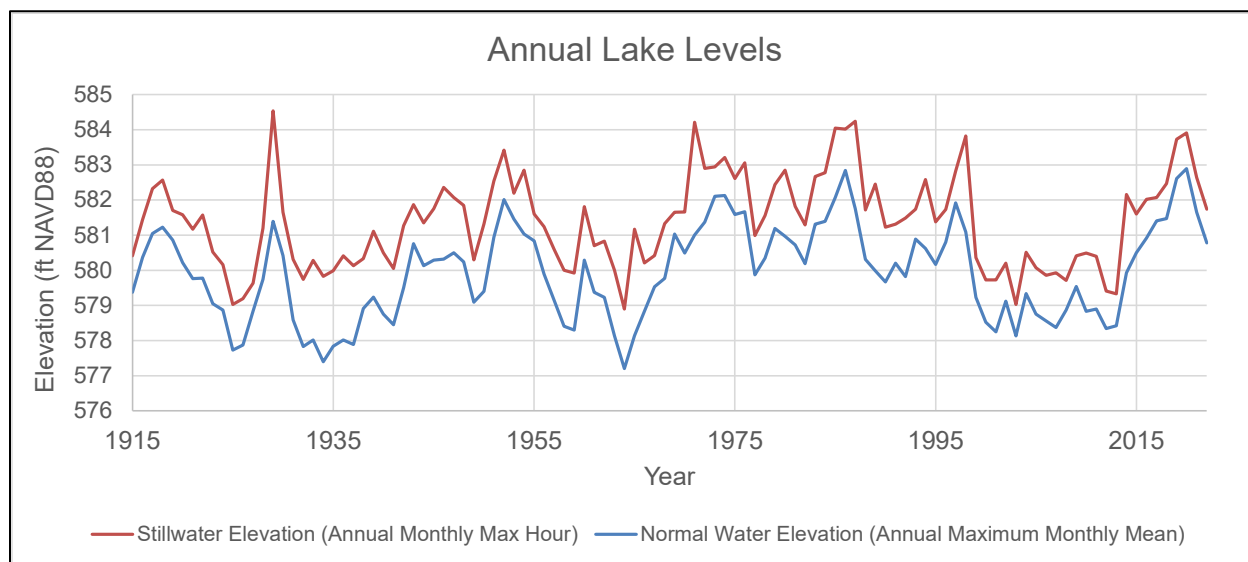
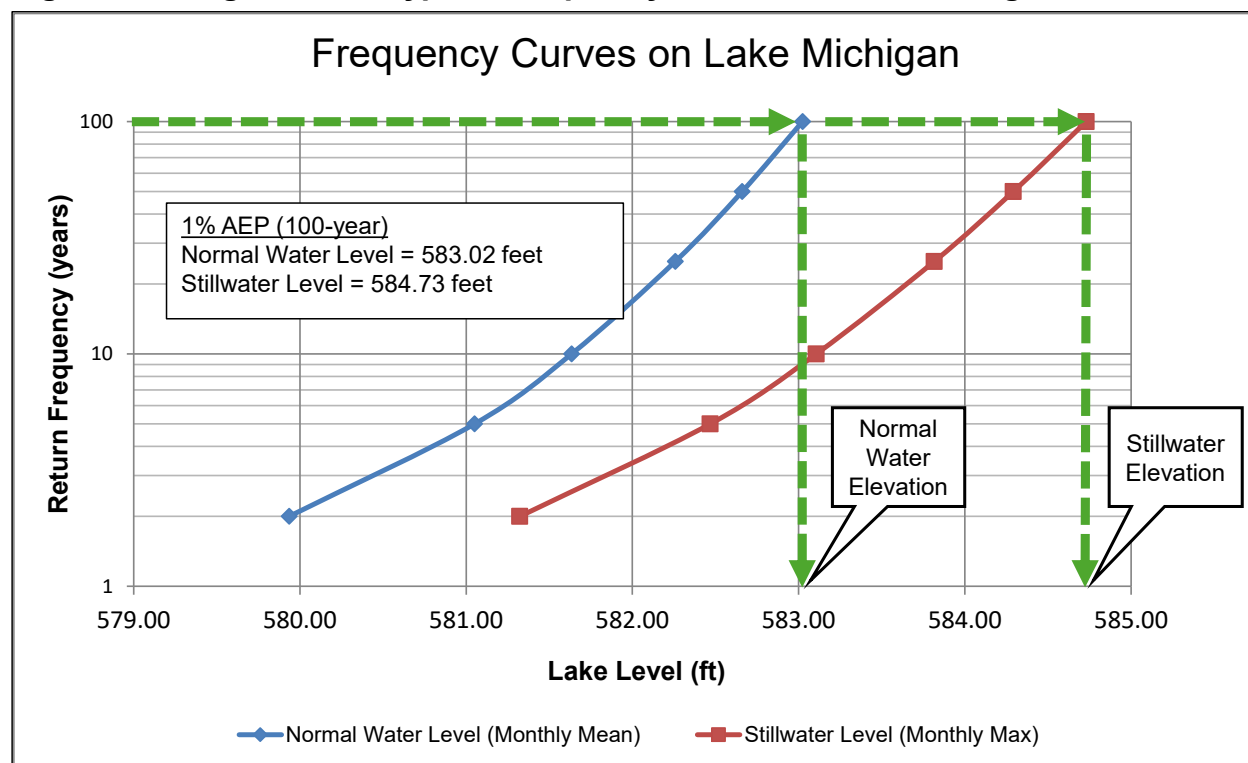


Table 9-2. Design Water Levels

Design AEP (ARI)	Normal Water Elevation (NAVD88)	Stillwater Elevation (NAVD88)
50% (2-year)	579.93	581.32
20% (5-year)	581.05	582.47
10% (10-year)	581.63	583.10
4% (25-year)	582.26	583.82
2% (50-year)	582.66	584.29
1% (100-year)	583.02	584.73

Figure 9-6. Log-Pearson Type III Frequency Curves on Lake Michigan

9.4.1.4 Determining Wave Height

Waves are one of the major forces affecting coastal systems including roads and bridges. Large, damaging waves occur during storms. Waves can generate tremendous forces and cause considerable damage when they are superimposed on top of storm surge and are able to impact roads and bridges.

Waves are the most significant factor to cause shoreline change. The energy from waves and wind can cause a rapid change in the shape and dimensions of the shoreline. As waves move from offshore to the beach, they often break, reform, and break again. The process of breaking waves results in a portion of the wave energy being dissipated. Additional energy is dissipated on the beach with the resultant transport of the beach sediment.

9.4.1.4.1 Depth-Limited Waves

The wave height as it approaches the shore and coastal infrastructure is critical to design. Coastal infrastructure along the Great Lakes is often located where the depth is shallow and the largest storm waves break as a result of depth-limited waves. In this scenario, the design wave height can be calculated using **Equation 9.1** and the wave crest elevation can be determined using **Equation 9.2**. A depth-limited wave breaking in shallow water is shown in **Figure 9-7**. Bathymetric survey is used to determine the depth near the coastal structures.

$$H = 0.8d \quad (9.1)$$

Where:

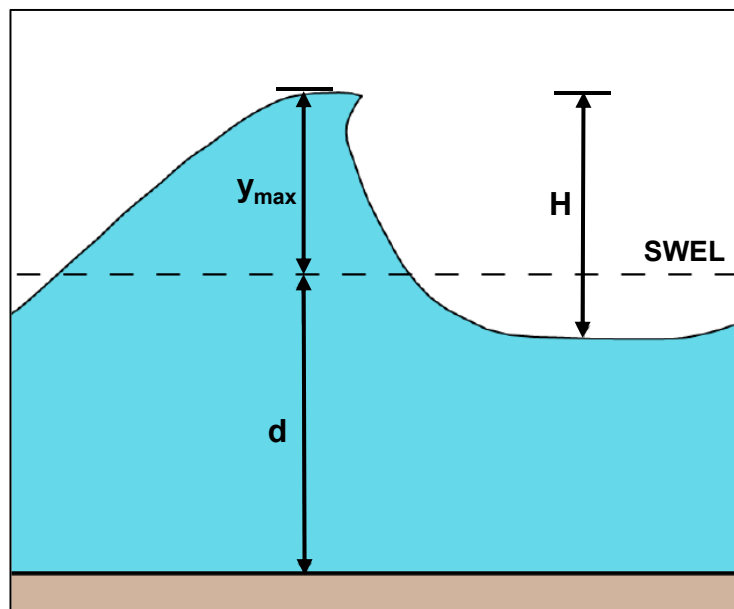
H = maximum breaking wave height, ft
 d = depth of water, measured from the SWEL to the revetment toe, ft

$$y_{\max} = 0.6d \quad (9.2)$$

Where:

$y_{\max}$ = difference between the SWEL and the depth-limited wave crest elevations, ft

Figure 9-7. Depth-limited Wave Breaking in Shallow Water (FHWA HEC-25, 2020)



9.4.1.4.2 Non-Depth-limited Waves

Waves striking coastal infrastructure are often depth-limited. When the wave height to depth ratio is less than 0.78 or the nearshore slope is greater than 1/15, the waves are not depth-limited. In Michigan, examples of non-depth-limited areas are Petoskey, Harbor Springs along M-119, and Port Austin. In areas where waves are not depth-limited, the design wave height is the significant wave height (H_s), the average height of the one-third highest waves. The significant wave height is generated with a numerical wave model. The model also considers wind speed, wind duration, fetch length, and water depth. The level of effort used to predict design waves correlates with the level of importance of a roadway or bridge structure. For major bridges and evacuation routes exposed to potentially large waves, a numerical wave model is employed to provide a sophisticated estimate of expected wave parameters. Refer to FHWA HEC-25 (2020, Chapter 5) for more information on wave theory and wave modeling.

9.4.2 Shoreline Infrastructure Impacts

This section provides guidance on identifying impacts associated with high water levels and waves along with design strategies to mitigate these risks.

9.4.2.1 Coastal Roadway Impacts

Coastal roadways are roads influenced by their proximity to shorelines that are impacted by water level, wave, and sediment transport environment unique to a coast. The coastal environment in Michigan includes the Great Lakes and any other water bodies affected by SWEL and waves. There are a number of state highways that are located within Michigan's coastal environment. Some roads are perpendicular to the coast and may serve as ingress and egress routes. Some roads are parallel to the coast either right along or inland from the shore. Some roads are major highways that run across or along bays or rivers.

Although the elevation of the roadway relative to the adjacent water level is a significant part of identifying risk, elevated roadways situated on bluffs prone to erosion are also at risk. The toe of the bluff is at the highest risk of erosion. Erosion of the toe undermines the entire bluff face.

The challenges for coastal roads are water level change, storm surge (seiche) which can lead to overtopping, undermining due to shoreline erosion, and damage due to wave impacts.

Roadway risk can be mitigated by raising the roadway, relocating the roadway inland, and/or adding revetment protection. The selection of risk mitigation is dependent on several factors including source of risk, configuration of the roadway relative to the waterbody, the criticality of the roadway, and the cost of risk mitigation.

9.4.2.1.1 High Water Level Risk

High water levels can put roadways and bridges at risk if the roadway is low relative to the adjacent water level. These risks may be long-term lasting several months or years or short term due to storm surge. In addition to direct roadway impacts, the drainage system, including open channels, storm sewers, and culverts, may be impacted by high water levels. Evaluate the drainage system to ensure positive drainage from the system via gravity without backwater impacts on the roadway. If necessary, pumping may be required to mitigate backwater through the drainage system.

Normal water levels can rise and remain elevated for months or years resulting in sustained inundation and flooding of the roadway. Under these conditions the roadway is impassable. The depth of flooding and the risk of damage increases because of storm surge and waves. This includes roadways adjacent to the Great Lakes or any directly connected water body whose water level fluctuates with the Great Lakes.

The SWEL is a short-term increase on water level above the normal water level due to storm surge and wave setup. The duration of these increases in water level are

measured in hours and days. During these short-term water level increases, a roadway that was dry under normal water levels can be overtopped. In Michigan, the elevation of a roadway is selected based on the design AEP to avoid overtopping. The seasonal and historical fluctuations of the Great Lakes and storm surge are taken into account when determining the roadway elevation. The MDOT Geotechnical Manual provides guidance on setting the roadway elevation above expected high water levels to provide acceptable long-term performance. The geotechnical and hydraulic engineer should work closely together in these situations to meet the design AEP.

If a roadway is expected to be overtopped during high water, armor the embankments to protect against erosion due to the flow of water across the road and due to wave action. Roadways may accumulate several feet of sediment that are required to be cleared off after the storm to restore roadway usage. For roadways that are planned to experience periodic inundation, contact the Geotechnical Services Section and/or the Pavement Operations for guidance.

In some situations, the roadway is above the SWEL but still low enough to have roadway drainage impacts. In these situations, evaluate the drainage system for sediment accumulation, low velocity, and other backwater impacts.

9.4.2.1.2 Low Water Level Risk

Low water levels in coastal areas may increase erosion and impact coastline infrastructure by exposing previously submerged areas to wave action. In areas where rivers are discharging to a large body of water, low water levels can cause a reduction in the river invert which may lead to increased scour risks, bank erosion, head cutting and long-term degradation. In areas with coastal revetments, low water levels may contribute to changes in littoral drift characteristics and increased wave action at the toe of a revetment, leading to toe undermining and structure failure. Other coastal infrastructure that may be impacted due to low water levels are bridges, roadways, culverts, and storm sewer outlets.

9.4.2.1.3 Undermining Due to Erosion Risk

Sediment transport along a shoreline may remove soil that is protecting a beach leading to shoreline or bluff erosion and making it susceptible to damage by wave action. The need for shore protection structures is generally limited to highways located along shorelines or at the top or bottom of bluffs that have a history of sloughing.

There are multiple options to protect roadways that are threatened by shoreline erosion. One option is to relocate or abandon the road. This option may be prohibited based on cost, access requirements, potential legal issues, and availability of land.

Another option is to employ shoreline stabilization to protect a threatened road. Stabilization provides protection from erosion associated with wave impacts. There are “hard” stabilization options such as a seawall or revetment. General guidelines for revetment design are covered in this chapter. Seawall design is beyond the scope of

this document. Assemble a multi-disciplinary design team when considering this type of design.

There are “soft” stabilization options that mimic characteristics of natural features such as coastal green infrastructure. “Soft” stabilization options often do not provide the level of protection needed to satisfy the design AEP and are generally not recommended.

9.4.2.1.4 Wave Impact Risk

Wave action is an erosive force affecting coastal infrastructure. Evaluate wave attack for embankments, abutments, and roadways near the shoreline. When identifying areas that are vulnerable to wave forces, peak wave heights are evaluated with the design SWEL AEP.

9.4.2.1.5 Littoral Drift

When waves break at an angle relative to the shoreline, a longshore current can develop in the breaker zone. The longshore current can move a large amount of sediment down the coast, also known as littoral drift. Shorelines are constantly changing in response to wave conditions. Shorelines accumulate and recede over time in response to the changes. Sediment deposits may interrupt and realign streams entering the water body as shown in **Figure 9-8**.

Figure 9-8. Au Train River Outlet to Lake Superior Near M-28 Migration Over Time



9.4.2.1.6 Long-Term Shoreline Recession

Long-term shoreline recession occurs due to erosion. FHWA HEC-25 (2020, Chapter 8) outlines a process for how to assess and design for roads in areas subject to long-term receding shorelines. It describes how long-term shoreline changes are quantified and used to estimate future positions. Additions and modifications of roads and revetments in coastal areas may impact long-term shoreline changes as well. Understanding and planning for shoreline changes is crucial for roadway projects and revetment design.

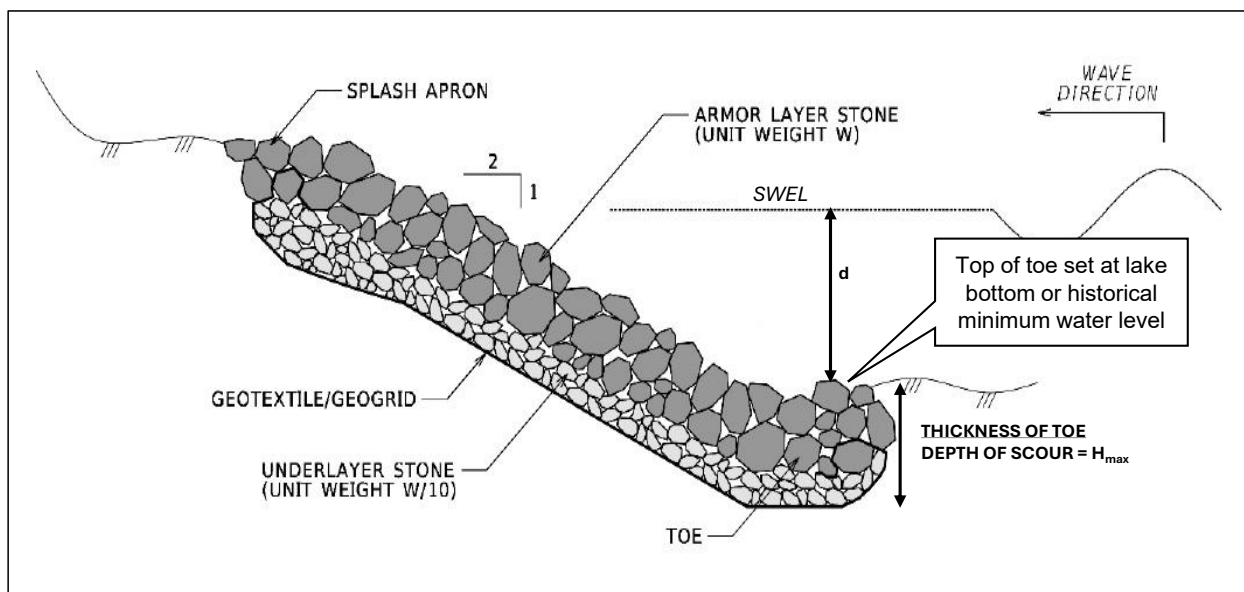
9.4.2.2 Coastal Roadway Revetment Design

Contact the Region Resource Specialist on trunkline projects to utilize the early coordination process between MDOT and EGLE to address environmental concerns. The coordination process may impact the final revetment design.

9.4.2.2.1 Revetment Design

Revetments are layers of protection placed directly on an existing slope, fill embankment, or dike to protect the area from waves and strong currents. There are many different types of revetments including layered armor stone revetments, berm revetments, concrete block revetments, etc. The layered armor stone revetment is a common and effective design and is discussed in this chapter. There are three components of a layered armor stone revetment: a stable armor layer, underlayer stones with a geotextile liner, and toe protection. The armor layer absorbs the wave energy. The underlayer of stones and the geotextile liner prevent the erosion of underlying soils. Based on the local geology, the natural soil may serve as the underlayer. Work with a geotechnical engineer to determine if the natural soils are suitable to serve as the underlayer. The toe protection prevents undermining due to erosion and supports the armor and underlayer. A typical coastal revetment cross-section is shown in **Figure 9-9**.

Figure 9-9. Typical Coastal Revetment Cross-Section (FHWA HEC-25, 2020)



Coastal layered armor stone revetments are designed using Hudson's equation to size the armor stones to withstand the approaching waves. While Hudson's equation is the recommended standard equation for revetment design, other methods, such as the Van der Meer equation, can be used to design revetments with approval from the Hydraulic Unit Supervisor on trunkline projects. These alternative methods are discussed in the *USACE Coastal Engineering Manual (CEM)* (2002). The Hudson's equation accounts for design wave height, structure slope, and stone density and angularity. Hudson's equation has no factor of safety. Refer to Section 7.3 in FHWA HEC-25 (2020) to understand the limitations of the Hudson's equation. MDOT recommends selecting a material with a specific gravity of 2.5. The following equations used in revetment design are discussed in FHWA HEC-25 (2020).

The median weight (Hudson's equation) for the armor layer of stone is:

$$W_{50} = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot \theta} \quad (9.3)$$

Where:

- W_{50} = median weight of armor stone, lb
- w_r = unit weight of stone, lb/cft (156 lb/cft)
- H = design wave height, ft
- K_D = empirical stability coefficient (= 2.2 for riprap gradations)
- S_r = specific gravity of stone (2.5)
- θ = slope angle, degrees

If the waves are depth-limited, the depth-limited maximum wave height is used. If the waves are non-depth-limited, the average of the highest 10% of all wave heights ($\overline{H_{10}}$). $\overline{H_{10}}$ is related to the significant wave height (H_s) by a factor of 1.27. As discussed in **Section 9.4.1.4**, the significant wave height is the average height of the one-third highest waves and is generated from a numerical wave model.

Revetment armor stones are generally more stable if placed on a milder slope and this is reflected in Hudson's equation. Steeper slopes call for larger, heavier stones. The maximum recommended slope for MDOT coastal infrastructure is 1V:2H.

The stone gradations recommended for coastal revetment riprap are narrower than those typically called for in non-coastal environments. The gradation recommended for the Hudson's equation is shown in **Equation 9.4**. This gradation avoids smaller stones that are used in other riprap applications that would not withstand the wave attack and could lead to revetment failure.

$$0.125W_{50} < W < 4W_{50} \quad (9.4)$$

Where:

- W_{50} = median weight of armor stone, lb
- W = weight of all the armor stones in the revetment, lb

The underlayer of rocks under the armor layer has a median weight no smaller than one-tenth that of the armor layer stones as shown in **Equation 9.5**:

$$W_{50, \text{underlayer}} = \frac{1}{10} W_{50} \quad (9.5)$$

Where:

- $W_{50, \text{underlayer}}$ = median weight of underlayer stone, lb

Equation 9.6 is used to estimate the equivalent diameter of the median stone weight:

$$D_{50} = 1.15 \left(\frac{W_{50}}{w_r} \right)^{1/3} \quad (9.6)$$

Where:

$$\begin{aligned} D_{50} &= \text{median size of armor stone, ft} \\ W_{50} &= \text{median weight of armor stone, lb} \\ w_r &= \text{unit weight of stone, lb/cft (156 lb/cft)} \end{aligned}$$

Local scour at the toe of the revetment is the most frequent cause of revetment failure. To avoid failure, the top of the toe is located at an elevation equal to the lake bottom or below the historical minimum water level, whichever is higher. The lake bottom is assumed to be where the shoreline slope intersects the slope of the lake bottom. In depth-limited designs, the toe may be set at a higher elevation. Contact the Hydraulic Unit Supervisor to finalize the elevation of the top of toe on trunkline projects.

The thickness of the toe is equal to the depth of scour. The scour depth due to depth-limited waves is approximately equal to the maximum wave height at the revetment as shown in **Equation 9.7**. If the waves are not depth-limited at the revetment follow suitable equations for scour depth found in the USACE CEM (2011, Part VI-5-3).

$$d_s = H_{\max} \quad (9.7)$$

Where:

$$\begin{aligned} d_s &= \text{depth of scour, ft} \\ H_{\max} &= \text{maximum wave height, ft} \end{aligned}$$

The thickness of the armor and underlayer are calculated using **Equation 9.8**. A rule of thumb in coastal design is that the armor layer is at least two stones thick.

$$t = n \left(\frac{W_{50}}{w_r} \right)^{1/3} \quad (9.8)$$

Where:

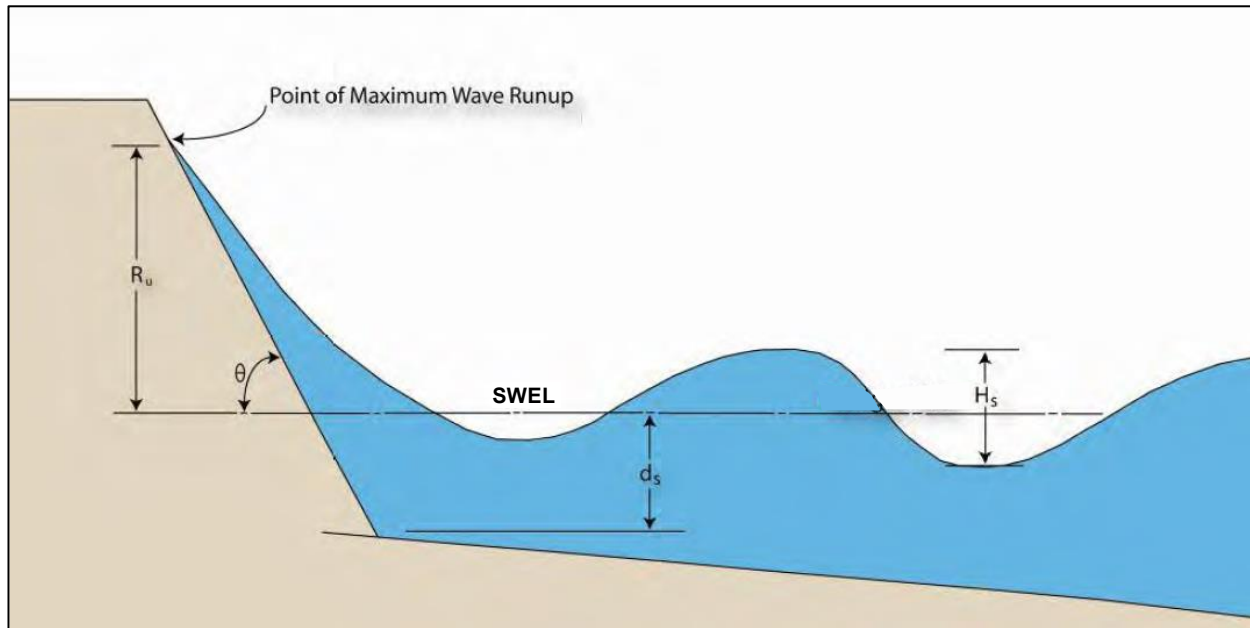
$$\begin{aligned} t &= \text{thickness of stone layer, ft} \\ n &= \text{number of stones per layer (at least 2)} \\ W_{50} &= \text{median weight of armor stone, lbs} \\ w_r &= \text{unit weight of stone, lb/cft (156 lb/cft)} \end{aligned}$$

For more information on using the Hudson's equation refer to FHWA HEC-25 (2020).

9.4.2.2.2 Wave Runup

When waves break on a sloping structure like a revetment, water runs up the structure potentially overtopping it. The height the wave travels above the SWEL on the revetment is called runup. Wave runup on a structure is shown in **Figure 9-10**. Determining the wave runup influences the height of the revetment. The top of the revetment is at an elevation greater than the wave runup elevation and the FEMA Zone VE elevation. The height of wave runup is estimated using **Equation 9.9**. The wave period is needed to determine runup. On the Great Lakes, waves typically have a period of 3-5 seconds.

Figure 9-10. Wave Runup on a Structure (FHWA HEC-25, 2020)



$$\frac{R_{u,2\%}}{H_s} = 1.6r\xi_{op} \quad (9.9)$$

Where:

- $R_{u,2\%}$ = runup level exceeded by 2% of incoming waves, ft
- H_s = significant wave height near the toe of slope, ft
- r = roughness coefficient ($r = 0.55$ for the stone revetments)
- ξ_{op} = surf similarity parameter as defined in **Equation 9.10**

$$\xi_{op} = \frac{\tan \theta}{\sqrt{2\pi H_s / g T_p^2}} \quad (9.10)$$

Where:

θ = angle of slope of structure, degrees (refer to **Figure 9-6**)

H_s = significant wave height near the toe of slope, ft

T_p = wave period, peak period, sec

g = acceleration of gravity, ft/s²

9.4.2.2.3 Example Revetment Design

A coastal roadway runs near a coastline. Shoreline erosion threatens to undermine the roadway. Design a revetment to protect the roadway from erosion. The top of roadway is set at 592. The design SWEL is 584.73 feet. The minimum historical water level is 579.73 feet. The water depth at the top of the toe of the proposed revetment is 5 feet. Assume a wave period of 5 seconds. Use a stone with a specific gravity of 2.5. Elevations given are in NAVD88.

Step 1: Determine design wave height

In this scenario, the largest waves are depth-limited. **Equation 9.1** is used to calculate the design wave height

$$H = 0.8d$$

$$H = 0.8(5 \text{ feet})$$

$$H = 4 \text{ feet}$$

Step 2: Specify slope, specific gravity and weight of stone

The slope of the revetment is 1V:3H (18.4 degrees). The stone used for the revetment has a SG of 2.5 and a unit weight of 156 lb/cft.

Step 3: Use Hudson's equation (**Equation 9.3**) to determine armor stone median weight

$$W_{50} = \frac{w_r H^3}{K_D (S_r - 1)^3 \cot \theta}$$

$$W_{50} = \frac{(156 \text{ lb/cft})(4 \text{ feet})^3}{(2.2)(2.5 - 1)^3 \cot(18.43)}$$

$$W_{50} = 448 \text{ lb}$$

This is rounded up to 450 lbs.

Step 4: Specify armor stone weight gradation using **Equation 9.4:**

$$0.125 W_{50} < W < 4W_{50}$$

$$0.125(450 \text{ lb}) < W < 4(450 \text{ lb})$$

$$56 \text{ lb} < W < 1,800 \text{ lb}$$

Step 5: Determine corresponding design armor stone median size using **Equation 9.6:**

$$D_{50} = 1.15 \left(\frac{W_{50}}{w_r} \right)^{1/3}$$

$$D_{50} = 1.15 \left(\frac{450 \text{ lb}}{156 \text{ lb/cft}} \right)^{1/3}$$

$$D_{50} = 1.6 \text{ feet}$$

Step 6: Specify the minimum armor layer thickness using **Equation 9.7:**

Assume $n = 2$ stone per layer.

$$t = n \left(\frac{W_{50}}{w_r} \right)^{1/3}$$

$$t = 2 \left(\frac{450 \text{ lb}}{156 \text{ lb/cft}} \right)^{1/3}$$

$$t = 2.8 \text{ feet}$$

This is rounded up to 3 feet.

Step 7: Determine level of runup

First determine the surf similarity parameter defined in **Equation 9.10:**

$$\xi_{op} = \frac{\tan(18.4)}{\sqrt{2\pi(4 \text{ feet})/g(5 \text{ sec})^2}}$$

$$\xi_{op} = 1.88$$

The height of wave runup is determined with **Equation 9.9**:

$$\frac{R_{u,2\%}}{H_s} = 1.6r\xi_{op}$$

$$R_{u,2\%} = 1.6r\xi_{op}H_s$$

$$R_{u,2\%} = 1.6(0.55)(1.88)(4 \text{ feet})$$

$$R_{u,2\%} = 6.6$$

The largest waves are expected to reach the SWEL elevation plus the height of wave runup, 584.73 feet + 6.6 feet = 591.33 feet. The roadway will not be overtopped because the runup is less than the elevation of the roadway, 592 feet.

Step 8: Specify toe protection

Toe protection is important to withstand scour and avoid revetment failure. The maximum wave height is used as maximum scour depth at the toe of the structure, 4 feet (refer to Step 1). The thickness of the toe is 4 feet.

Step 9: Specify underlayer

The median rock weight and equivalent diameter of the underlayer are calculated using **Equations 9.5 and 9.6**, respectively:

$$W_{50,\text{underlayer}} = \frac{1}{10} W_{50}$$

$$W_{50,\text{underlayer}} = \frac{1}{10} (450 \text{ lb})$$

$$W_{50,\text{underlayer}} = 45 \text{ lb}$$

$$D_{50,\text{underlayer}} = 1.15 \left(\frac{W_{50,\text{underlayer}}}{w_r} \right)^{1/3}$$

$$D_{50,\text{underlayer}} = 1.15 \left(\frac{45 \text{ lb}}{156 \text{ lb/cft}} \right)^{1/3}$$

$$D_{50,\text{underlayer}} = 0.77 \text{ feet}$$

The thickness of the underlayer is determined using **Equation 9.8**:

$$t_{\text{underlayer}} = n \left(\frac{W_{50,\text{underlayer}}}{w_r} \right)^{1/3}$$

$$t_{\text{underlayer}} = 2 \left(\frac{45 \text{ lb}}{156 \text{ lb/cft}} \right)^{1/3}$$

$$t_{\text{underlayer}} = 1.3 \text{ feet}$$

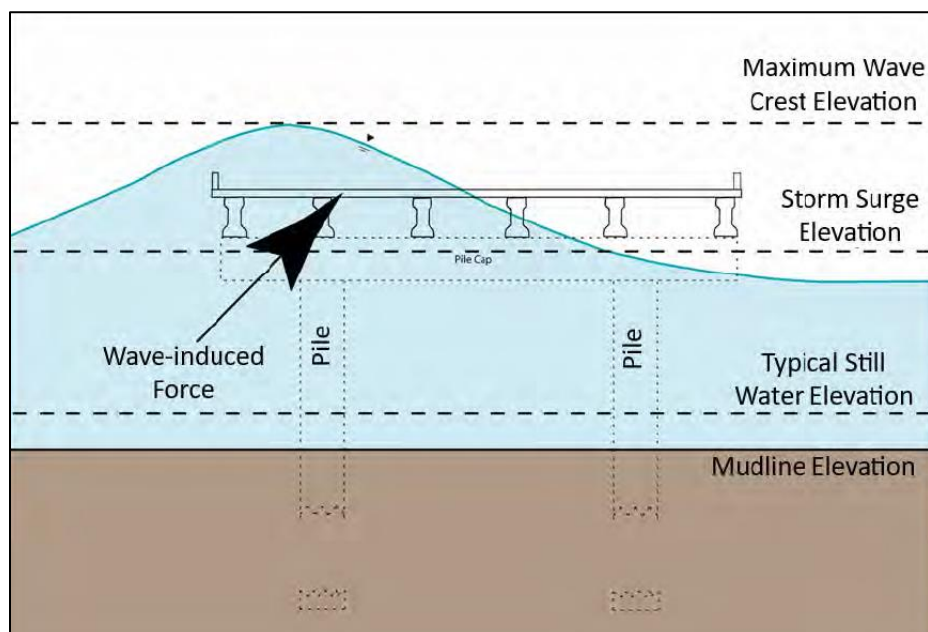
9.4.2.3 Coastal Bridge Impacts

Bridges in the coastal environment are impacted by wave loads on bridge decks and increased scour due to longshore currents and wave forces (refer to **Section 9.4.2.1** for more information). Bridges are located in a variety of settings in the coastal environment that present unique issues and challenges. In Michigan, coastal bridges are located over bays, at river outlets, or crossing rivers.

9.4.2.3.1 Wave Impacts

Wave loads are the primary forces causing damage to coastal bridges. The damage occurs as the SWEL rises to a level where the waves attack the bridge superstructure. The waves produce vertical (uplift) and horizontal forces which may exceed the weight of a bridge deck. The resultant force produced by a wave is shown in **Figure 9-11**. In addition to these wave loads, air pockets may become trapped under the bridge deck as the storm surge elevation increases. The air pockets increase the buoyancy of the bridge deck when it is submerged.

Figure 9-11. Wave Load Forces on Bridge (FHWA HEC-25, 2020)



The most common design approach to avoid superstructure wave forces is to elevate the bridge sufficiently above the maximum SWEL allowing the wave crests to pass under the low-chord of the bridge with 1 foot of freeboard. If a bridge is designed to

allow overtopping for the design criteria, it is required to be able to withstand the wave loads. FHWA HEC-25 (2020) provides design calculations for considering wave forces on coastal bridges.

9.4.2.3.2 Bridge Scour

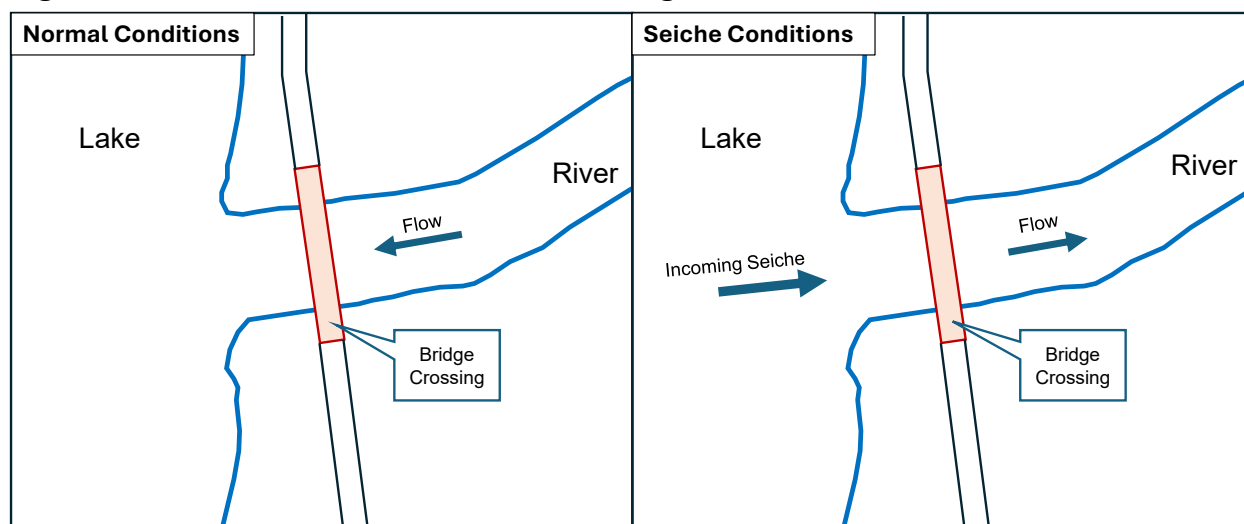
Coastal bridge scour occurs when bridge foundations, decks, abutments interact with currents and waves that alter sediment transport. In the Great Lakes region, coastal bridges experience increased scour due to large waves and seiches. The types of scour that occur include the same general categories (long-term change, contraction scour, and local scour) as found at riverine bridges (Refer to Chapter 6, Bridge Hydraulic Design, Section 6.4.5). In addition to Chapter 6, other resources on bridge scour due to coastal impacts include FHWA HEC-18 (2012, Chapter 9) and FHWA HEC-25 (2020, Chapter 12). Contact the Hydraulics Unit Supervisor to determine if a qualified coastal engineer with extensive experience in coastal hydrodynamics, wave mechanics, and sediment transport is required when considering bridge scour due to coastal impacts on trunkline projects.

9.4.2.3.3 Bridge Scour Due to Waves

The presence of waves may increase scour at bridge abutments and piers. Waves move sediment and produce scour depressions at bridge foundations. The wave reflection from abutment walls or waves breaking at the abutments drives the scour. Typically, scour due to waves in shallow water is more severe near abutments and seawalls than at piers. Scour is greater in magnitude from breaking waves. Waves cause further scour when water levels are elevated, causing waves to impact approach embankments. Waves easily remove embankment soil and undersized riprap during these scenarios. The USACE CEM provides methods for estimating scour at abutments due to regular, irregular, nonbreaking, and breaking waves and on piers using local pier scour equations. Wave-induced scour occurs over a shorter amount of time than scour in riverine conditions. Due to this short time frame, the equations for scour can be overly conservative.

9.4.2.3.4 Bridge Scour Due to Seiche

When a seiche occurs during a storm surge, riverine flows entering the lake may reverse flow as shown in **Figure 9-12**. In this case, the seiche overwhelms the riverine discharge and the flow is in the upstream direction caused by the incoming seiche. Increased scour due to a seiche may occur during the rising or recession of a seiche event. During the recession of an event when the seiche water level recedes, the coastal flow and the riverine flow combine which may result in higher velocities and increased scour. Scour from the incoming and receding seiche is considered and the greater scour is used for design.

Figure 9-12. Seiche Flow Near Coastal Bridge**9.4.2.3.5 Scour Evaluation Methods**

FHWA HEC-25 (2020, Chapter 12) describes a process for bridge scour evaluation and recommends scour evaluation in the Great Lakes coastal environment to follow the method for tidally-dominated bridge scour. This method considers the unique impact of seiches on scour. In this scenario, scour is evaluated for riverine (standard scour analysis, refer to Chapter 6) and seiche events to determine which one generates the most scour and governs the design. A two-dimensional unsteady hydraulic or hydrodynamic model, such as SRH-2D, is recommended when evaluating bridge scour due to seiches. Contact the Hydraulics Unit Supervisor to determine if a qualified coastal engineer with extensive experience in coastal modeling is required when determining coastal scour impacts on trunkline projects.

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